

Extreme X-ray / Optical Sources (EXOs): Probes of the High-Redshift Universe

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Summary of Observations (Chandra, HST, VLT)

X-ray / Optical Matching

Optically Undetected X-ray Sources

- Optical limits, IR detections
- X-ray fluxes: -> Extreme X-ray /Optical ratios (EXOs)

Possible explanations:

- Galactic objects (effectively ruled out)
- Low-z AGN in low-lum dwarf galaxies (unlikely)
- Intermediate-z EROs? ($z \sim 3-5$)
- High-z AGN? ($z > 6-7$)

Summary of Observations

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X-ray observations (Giacconi et al.; Brandt et al.):

- HDFN: 2 Msec; CDFS: 1 Msec

HST/ACS observations (GOODS):

- CDFS + HDFN: Each has 15 ACS fields (10"x16")
- B: (F435W) 3 orbits depth
- V,i: (F606W, F775W) 2.5 orbits depth
- z: (F850LP) 5 orbits depth (3σ AB \sim 28.4)

VLT observations (GOODS):

- ISAAC, SOFI: J \sim 25.9, H \sim 25.1, K \sim 25.0

Note: In this talk, focus on CDFS since HST/ACS data were complete earlier for this field.

CDFS main catalog (Alexander et al. 2003):

- Total of 225 sources (>10 counts in 1 Msec)

HST/ACS CDFS catalog (Giavalisco et al. 2003):

- z-band (deepest, cleanest): S-Extractor 10σ limit ~ 27.5

X-Ray/Optical Matching (Koekemoer et al. 2003):

- Applied astrometric corrections to entire X-ray catalog based on 104 “astrometrically clean” X-ray/ACS sources
 - Residual X-ray/HST differences $\sim 0.2''$ r.m.s.
- Resulting matches between X-ray/ACS:
 - Total of 195 X-ray sources matched to ACS within $1''$ (5σ)
 - Further 23 near fainter ACS sources (3 - 10σ z-band detections)
 - Finally, 7 sources with no ACS counterparts

No detections in HST/ACS images:

- z-band, as well as summed B+V+i+z
- Limits in 0.2"x0.2" aperture (4x4 pix, used by S-Extractor) are $\sim 0.0017\text{--}0.0024 \text{ cts s}^{-1} \text{ pix}^{-1}$, thus $3\sigma \text{ AB} \sim 27.9\text{--}28.4$

Detections in X-ray catalog robust:

- Faintest X-ray source has 25 counts
- Most have $\sim 40\text{--}50$ counts; brightest is 89 counts
- X-ray exposure maps are well behaved

Some detections in VLT images (SOFI/ISAAC):

- 4 have robust K detections (22.4 - 23.5), 2 marginal
- 3 have J detections, 5 have H detections

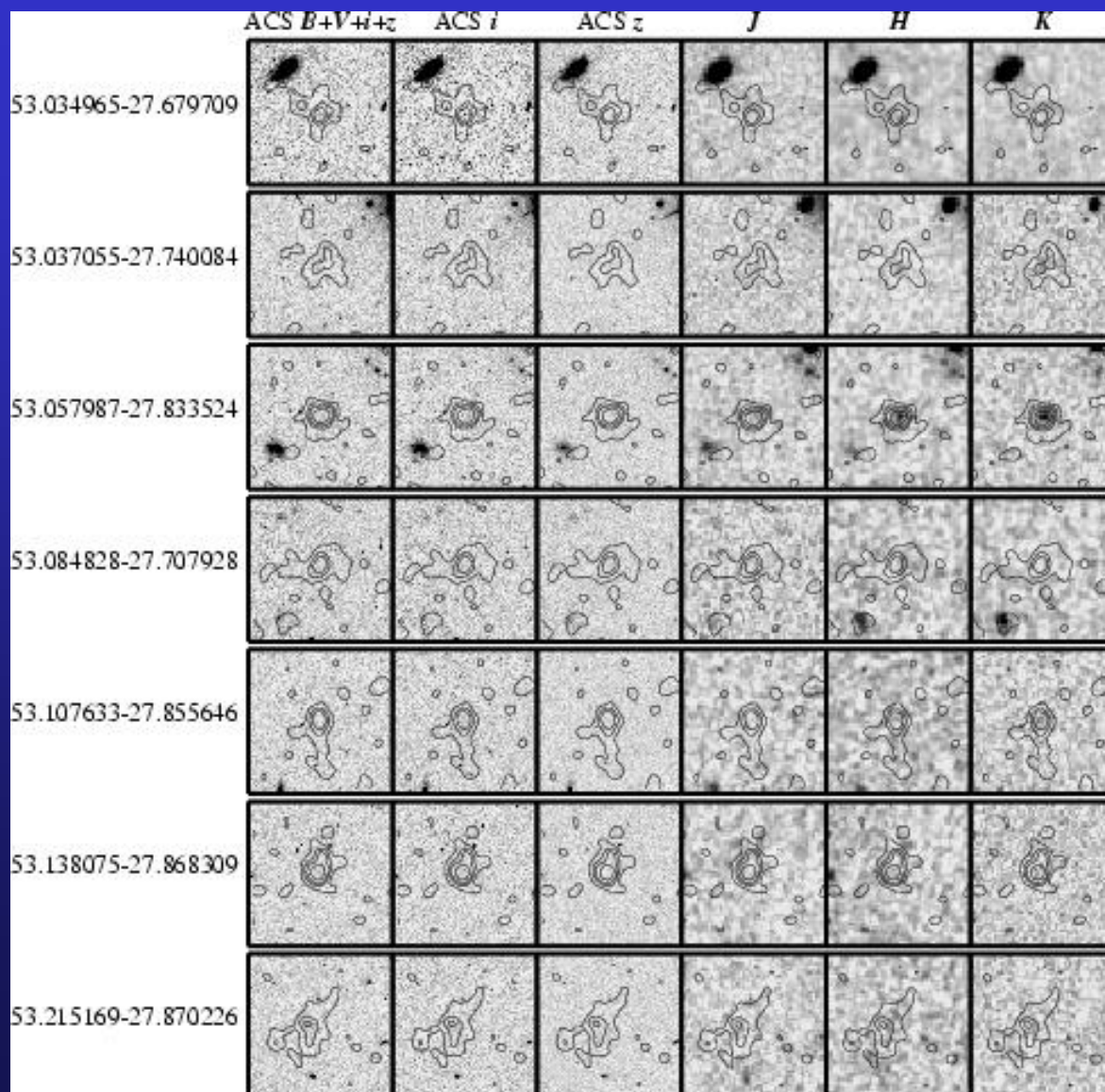
Optically Undetected Sources

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(Koekemoer et al. 2003
ApJL in press,
astro-ph/0306407)

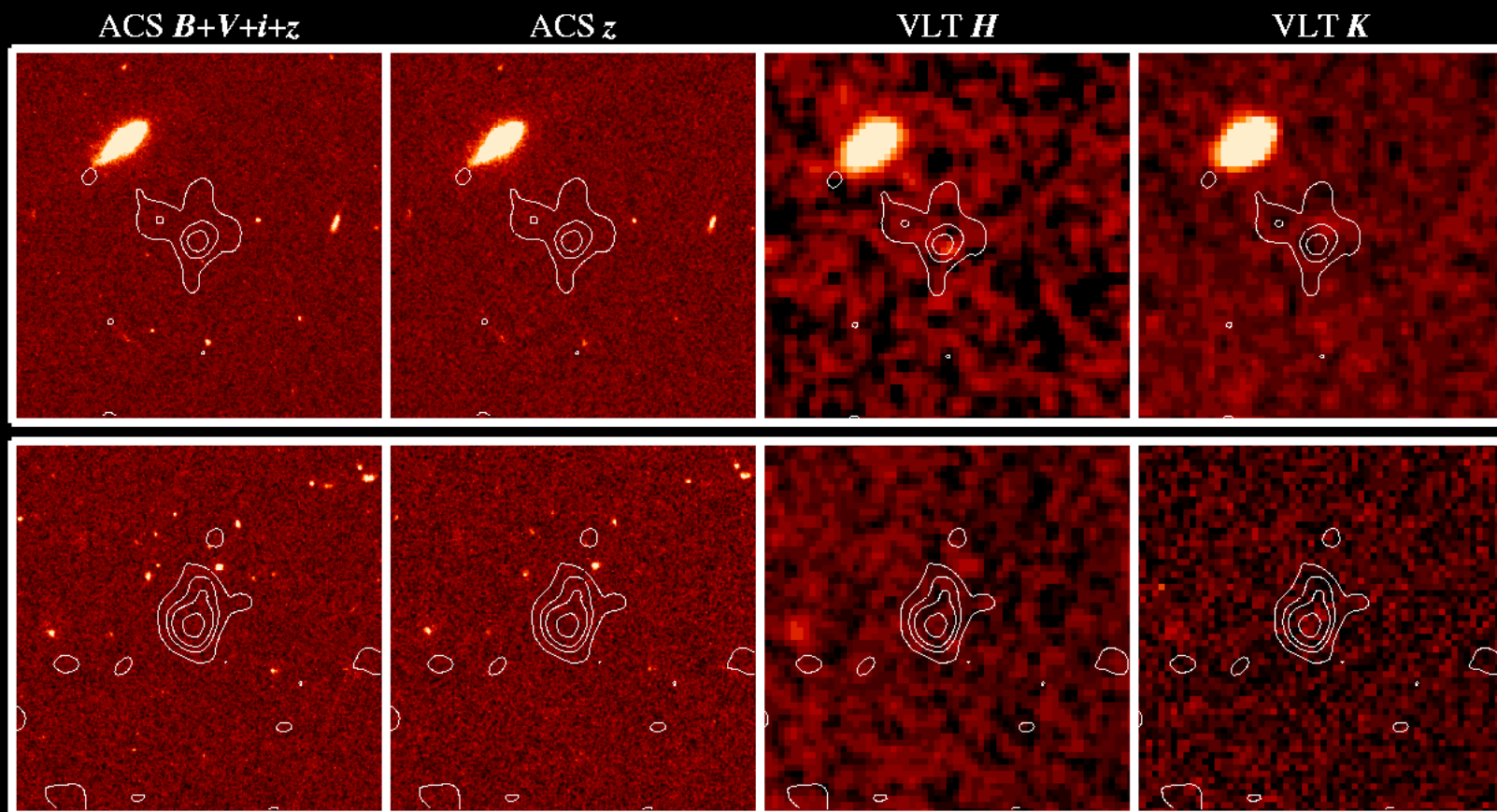
- Greyscale:
 - ACS, VLT
- Contours:
 - Chandra X-ray (0.5-8 keV)
 - Contours 1,2,3 σ then doubling
- K detections:
 - 4 significant
 - 2 marginal
- 3 J detections
- 5 H detections



Optically Undetected Sources

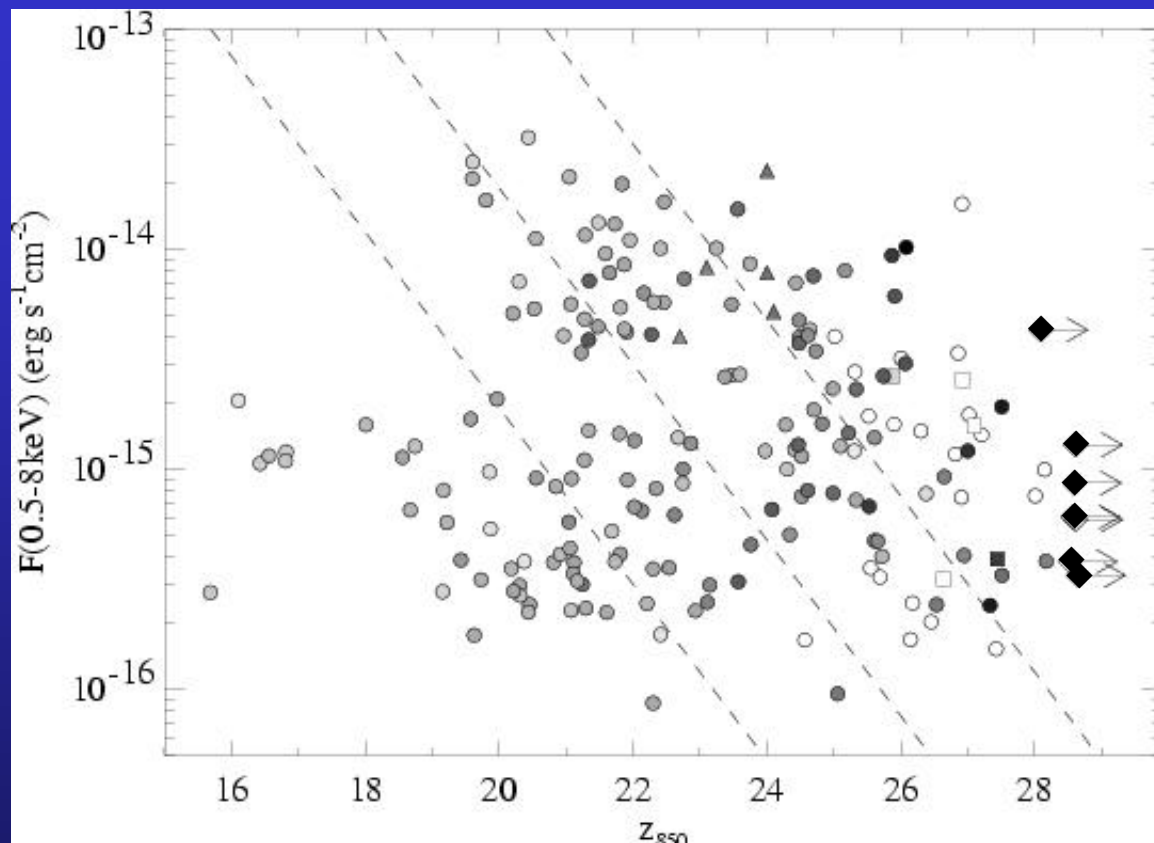
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Koekemoer et al. 2003, ApJL, accepted (astro-ph/0306407)

- Lines show F_X/F_{Opt} values of 0.1, 1, 10
- Greyscale = colour:
 - dark: high z-K
 - white: undetected in K
 - Redder sources have higher F_X/F_{Opt}
- Squares: Yan etal '03
- Triangles: LH ERO's
- Optically undetected sources have comparatively high F_X :
 - Not necessarily expected; \rightarrow relatively high F_X/F_{Opt}
 - Values of $F_X/F_{Opt} \sim 10 - 100$ times above most of the AGN

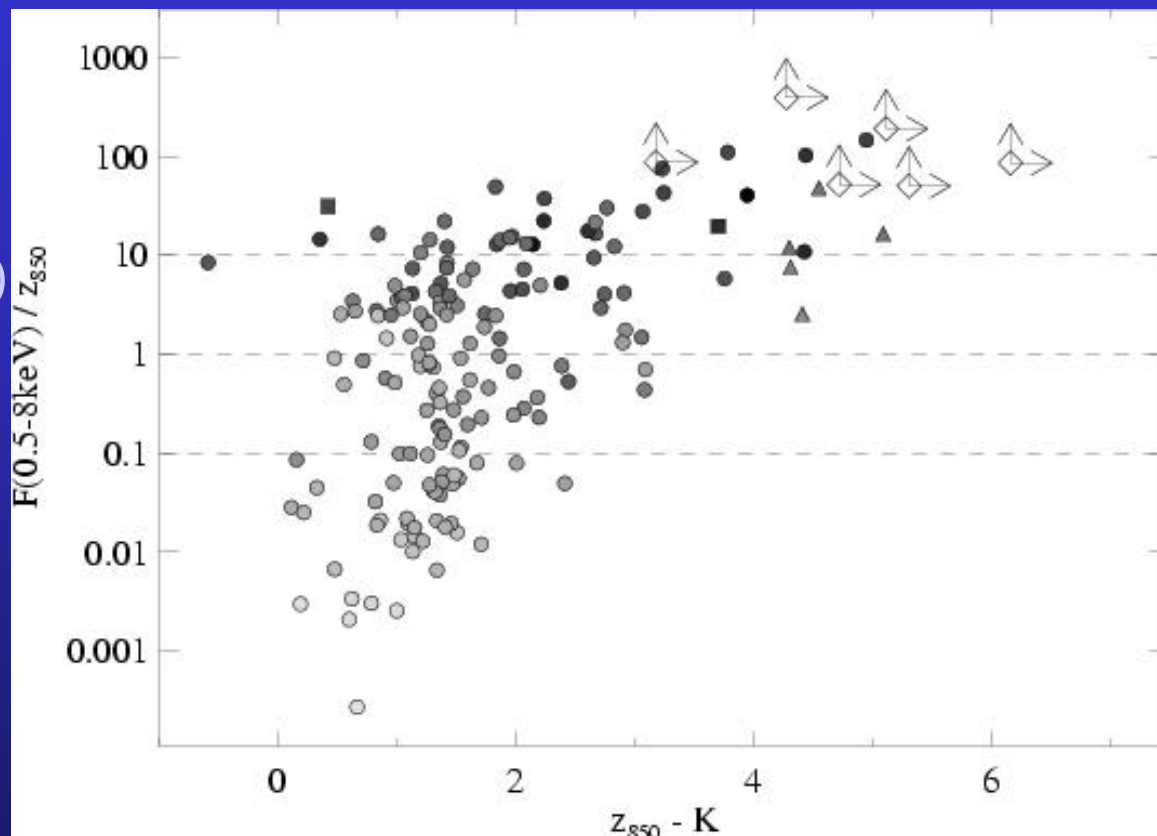


F_X/F_{opt} vs $z-K$

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- Symbol shading here shows z -band magnitude (darker sources are fainter; white undetected)
- Low F_X/F_{opt} sources:
 - Bluer, brighter
 - Generally lower- z sources
 - Mostly starbursts, normal galaxies
- $F_X/F_{opt} \sim 0.1-10$:
 - Cover full range of colours (Type 1 \rightarrow Type 2 AGN)
- Highest F_X/F_{opt} sources: tend to also be the reddest
- Reddest sources: tend to be those with highest F_X/F_{opt}



Need to explain:

- Relatively faint z-mag together with bright X-ray flux
- Relatively red colours (at least for those detected in K)

Galactic Sources?

- LMXB, CVs, etc: $L_X \sim 10^{30} - 10^{35} \text{ erg s}^{-1}$, which would be consistent with $\sim 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ at $\sim 10\text{-}100 \text{ kpc}$
- However, number density in our survey area (0.05 deg^2) implies numbers $\sim 10^4 - 10^5 \times$ too high for our galaxy

Low-z AGN?

- e.g., dwarf NGC4395: $M_B \sim -16.5$, $L_X \sim 3 \times 10^{38} \text{ erg s}^{-1}$
- z-band limits $\rightarrow DM \sim 45$, $\rightarrow F_X \sim 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2}$
 $\rightarrow 10^4 \times$ more lum. in X-rays – no known local analogs

Intermediate-z ($\sim 2-6$) EROs:

- Red colours – are they not just EROs?
- Simple stellar models (single-burst Bruzual & Charlot, metallicity $0.3Z_{\odot}$, with $H_0=0.65$, $\Omega_m=0.3$, $\Omega_{\Lambda}=0.7$):

Redshift	1	2	3	4	5	6
Age (Gyr)	5.7	3.2	2.1	1.5	1.2	0.9
z-K	1	4	4.5	3.5	3.2	3

- Colours can indeed be (barely) accounted for by EROs
- However, K-band magnitudes are still $\sim 100\times$ too low at each of these redshifts, compared with normal rest-frame F_X/F_{opt} for AGN: expect $K \sim 18-20$, not 23-25
- Needs high reddening for entire host galaxy ($A_V \sim 3-6$)

High- z ($>6.5-7$) AGN:

- Are the sources simply not just at higher redshift, so that $\text{Ly}\alpha$ is redshifted out of the z -band filter? ($z \sim 6.5-7$)
- Our sources are similar to those of Yan et al., just fainter. We detect all the Yan et al. sources, so agree with them that their sources are probably at lower z
- However, if our sources are a high- z extension of Yan et al. sources, then their DM is $\sim 1.5 - 2$ mag higher.
- If Yan et al. sources are E/S0 at $z \sim 3-5$, then the EXOs would be at $z \sim 6-10$. Then their hosts (from K-band) would have $U \sim -20$ to -21 , and $L_X \sim 2-6 \times 10^{44} \text{ erg s}^{-1}$
- These values are plausible for AGN, may be high- z extension of $z \sim 5$ XLF from Cristiani et al. (2003)

- An apparently new distinct population of sources: Extreme X-ray / Optical Sources (EXOs):
 - Undetected in z-band to very faint limits ($AB \sim 27.9-28.4$)
 - Higher F_x/F_{opt} (by $\sim 10-100\times$) compared with other AGN
- Rule out Galactic sources based on number counts
- Low-z, low-lum dwarfs with $10^4\times$ over-luminous AGN not ruled out completely - but no known local analogs
- Two most likely possibilities:
 - Colours consistent with $z \sim 2-6$ EROs, but faint K-band mags imply old, unusually low-luminosity hosts + large reddening
 - Could instead be at higher z ($>6.5-7$, i.e. $Ly\alpha$ redshifted out of optical filters); for $z \sim 7-10$ their absolute magnitudes & X-ray luminosities are compatible with a high-z extension of moderate-luminosity AGN, and relatively normal hosts